Development of New PSC Box Girder Bridge with Concrete-filled FRP Struts

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Abstract: *In this paper, the new type of PSC Box Girder Bridge with concrete-filled FRP struts is introduced. In order to verify the efficiency and superiority of this type of bridge, the investigation in structural and economical effectiveness, durability and appearance was performed. Finally, the merit point of this bridge type, strut attachment plan, and the analytical and experimental results are presented.*

Keywords: PSC box girder bridge, FRP strut, MSS method.

1. Introduction

In general, the 4 lane deck bridge type has been used with twin PSC box girder and two column piers. However, this type has some limitation to increase girder span length and improve aesthetic view because of massive super & sub-structure. In order to overcome the problem and achieve the better appearance, Incheon Bridge Approach Road section 3 which is located across the ocean lake park area of new Song-do city was designed by applying the concrete-filled FRP struts to single PSC box girder, so that it makes main structures more slender. It is the first time that the design and construction of FRP strut system for 4 lane box deck in 60m span length are applied for bridge construction in Korea.

2. Structural details

2.1 Girder cross section review

In order to decide the cross section type of PSC box girder, general investigation in structural and economical efficiency, appearance, construction possibility are performed with PSC box girder bridge attaching single rib and strut. As a results of this investigation, PSC box girder bridge with concrete-filled FRP struts is selected as the best efficient type in Incheon Bridge Approach Road section 3 because of the smaller value of deflection at cantilever, the efficiency of section at

transverse direction, lightweight super & sub-structure as well as possibility of use with MSS equipment in the construction site.

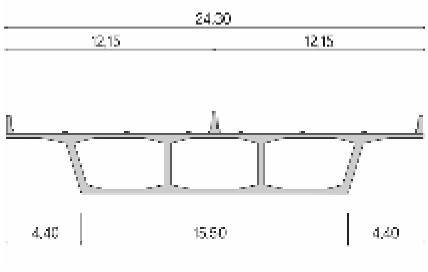
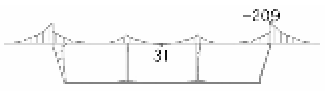
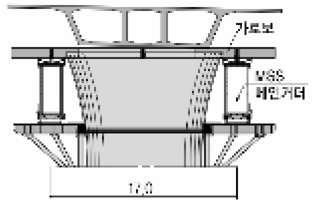
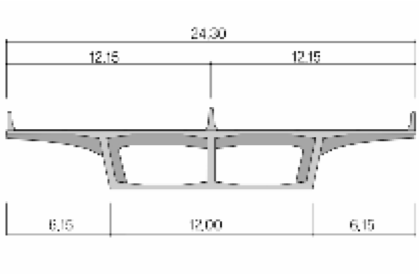
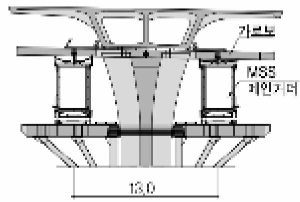
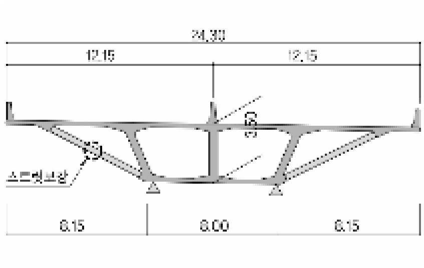
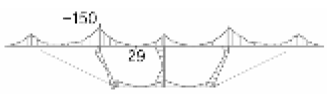
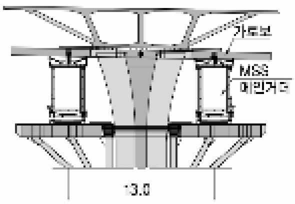
Comparison	Efficiency / Effectiveness	Appearance / Constructivility
1st plan : Traditional Box Girder (Old) 	<Midas Civil>  · Max. negative moment: -209kN·m · Max. positive moment: 31kN·m · Self weight: 433kN · Big substructure	 · Simple appearance · Requirement big MSS equipment for heavy weight girder
2nd plan : Box girder with cantilever rib (Present) 	<Midas Civil>  · Max. negative moment: -184kN·m · Max. positive moment: 28kN·m · Self weight: 416kN · Structural efficiency improvement due to rib & small substructure	 · Rhythmical sense with rib · Form-work difficulty due to rib casting parts
3rd plan : Box girder with struts (Innovative) 	<Midas Civil>  · Max. negative moment: -150kN·m · Max. positive moment: 29kN·m · Self weight: 388kN · Structural efficiency improvement due to struts & small substructure	 · Rhythmical sense with struts · Slim appearance · No additional process for strut installation using MSS method

Table 1. The comparison of various types of cross sections

2.2 The analysis of sectional efficiency of PSC Box girder with FRP struts

As a sectional effectiveness comparison between general PSC box girder and PSC box girder with FRP struts, as shown on Table 2, the PSC box girder section with FRP strut shows an amount of decrease in volume about 15% in super-structure and 50% in sub-structure, respectively. PSC box girder section with FRP strut as a lightweight super-structure is able to make the economical section for the sub structure.

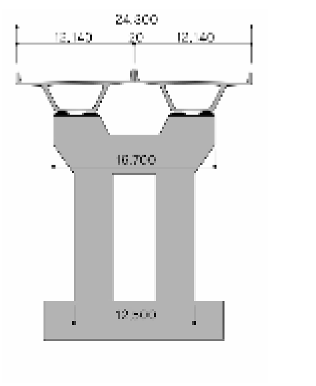
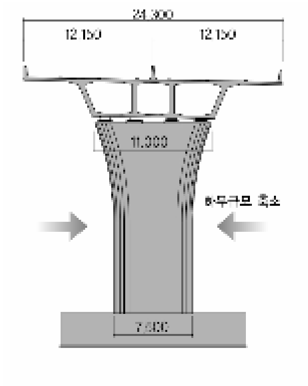
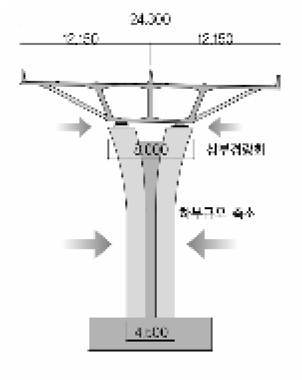
Twin Box Girder (Old)	Integrated One Box three-cell girder (Present)	Integrated strut section (Innovative)
		
· Upper cross section area : 15.855m^2 (1.0) · Coping cross section area : 58.450m^2 (1.0) · Column cross section area : 28.000m^2 (1.0)	· Upper cross section area : 16.74m^2 (1.05) · Coping cross section area : 38.50m^2 (0.66) · Column cross section area : 26.25m^2 (0.94)	· Upper cross section area : 14.50m^2 (0.91) · Coping cross section area : 23.88m^2 (0.41) · Column cross section area : 14.31m^2 (0.51)

Table 2. The efficiency comparison of cross sections

2.3 An advantage and characteristic of PSC box girder with FRP struts

The FRP coating strut structure is very effective comparing with the other types of structures. In general, concrete and steel are popularly used as strut materials. However, concrete strut is not beautiful and steel strut is very difficult to maintain because of corrosion and fatigue problems. To overcome these problems, PSC box girder with FRP strut is proposed in this paper. PSC box girder with FRP strut is possible to increase durability, to prevent corrosion as well as to improve aesthetic appearance. Also, FRP struts will be able to expect the role as the additional reinforcing stiffener.

1st generation(Old) **Concrete strut**	**2nd generation(Present)** **Steel pipe strut**	**3rd generation(Innovative)** **Concrete filled FRP strut**
· Low appearance due to concrete outer surface · Easy maintenance control due to no re-coating · Rebar exposure due to peel-off a coating	· Good appearance using various colorful application · Disadvantage due to re-coating · Fatigue disadvantage due to welding connections	· Application of FRP coating that is possible to paint · Material that is no need to re-coat · Effect of fall-off concrete control
SCARDON bridge(France) KOCHETAL bridge(Germany)	MEAUX(France) 芝川高架橋(Japan)	内牧高架橋(Japan)

Table 3. The Comparison of characteristics of strut material

3. Strut fabrication & construction plan

3.1 FRP strut fabrication

The FRP struts are fabricated in shop yard and then transported to the construction site for quality control to get the highest quality in the minimum construction time. For assurance of attachment, vibrators are used at the outside of strut. In consideration of concrete laitance, 5mm surplus at both sides are left

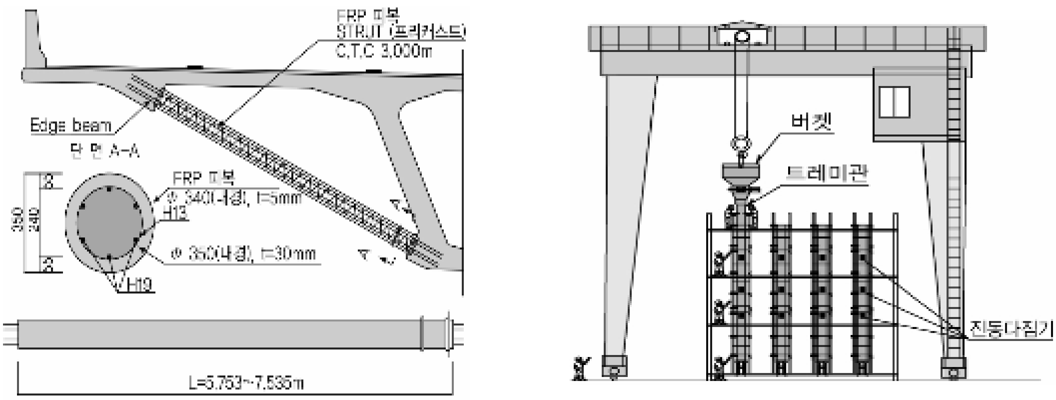


Fig 1. The FRP strut fabrication details

The procedure of FRP struts are as follows;

Procedure	Items
①	Install a coating protection at FRP coating pipe after fluorine covering
②	Insert a rebar mesh into FRP coating pipe
③	Install a steel form lid on base plate
④	Install a steel form lid on top plate
⑤	Pour concrete(FRP coating pipe is used as a substitute for form)
⑥	Carry out appearance & non-destructive test after curing concrete

Table 4. The procedure of FRP strut fabrication

3.2 The installation and transportation of FRP strut

Ready-made FRP struts in the factory when assembled in site are installed using the Gantry Crane. To prevent interference with steel reinforcing bars, the upper form is installed before assembling steel reinforcing bars in the top slab. Because the struts are continuously arranged at 3m interval, the forms in the locations of struts are planned as folding forms to break them up conveniently after upper concrete pouring.

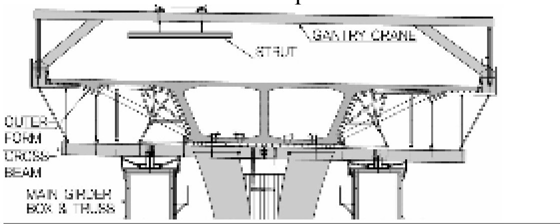
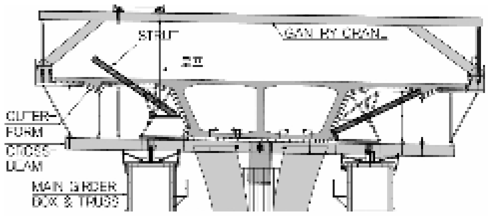
Strut Transportation	Strut Installation
	
· Strut transportation using cargo truck on construction load · Setting up constructing location using G/C attached MSS equipments	· Setting up regular position with descending rope of G/C · Joint combination using winch connected to strut after micro-adjustment

Table 5. The strut transportation & installation plan

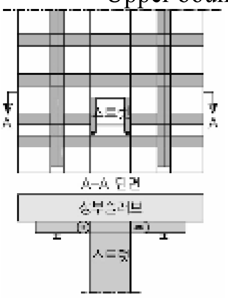
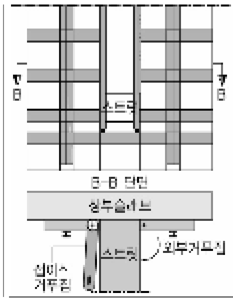
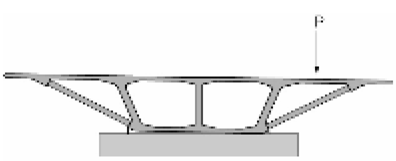
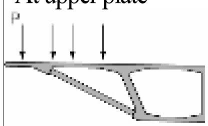
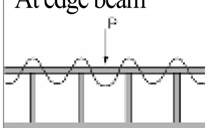
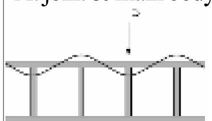
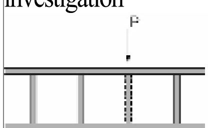
Strut installation & Upper bound construction stage		MSS equipment movement stage	
	· Making a folding form not to be interfered with struts during formwork		· Transporting strut with Gantry Crane attached MSS equipment and Inserting the strut to open part of the form, then Moving the form folded

Table 6. The management plan of outside form

4. Loading test of a real-size site model

In order to establish the validity of the FEM analysis results, the loading test of a real-size site model was carried out and detailed test procedures are included: loading test at upper plate, loading test at edge beam, loading test at joint & main body, fatigue test, damage investigation, and FRP strut capacity evaluation.

Summary	Loading test		Analysis
	· At upper plate 	· At edge beam 	· Verification of structural stability at upper plate and edge beam · Durability problem due to design load · Buckling stability analysis of strut · Comparison with 3-dimensional FEM analysis result · Fatigue analysis of strut joint · Structural stability analysis for damaged strut
· Key tests : loading test at upper plate, loading test at edge beam, loading test at joint & main body, damage investigation	· At joint & main body 	· Damage investigation 	

			➡ Verification of structural stability through loading test

Table 7. Analysis of loading test of a real-size site model

Fig 2. Loading test of a real-size site model

4.1 FRP strut capacity valuation

FRP struts are expected to be fractured at ultimate load. Therefore, to prevent the peeling off of the cover of concrete struts, the maximum thickness of FRP external tube is determined as 3.0mm even though the optimized design result is 1.8mm.

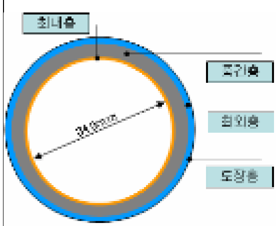
Contents				
	Layer	Function	Thickness	Constitutions
	Core layer	Chemical resistance of FRP about concrete alkali	0.5mm	Epoxy resin
	Mid layer	Shape preservation, internal force resistance	3.0mm	Glass fiber + Epoxy resin
	Outer layer	UV block, Decay/fire resistance, Preparation of repair/reinforcement in future	1.5mm	UV coating + Glass fiber + Epoxy resin
	Covered layer	Decay resistance, appearance	≥ 60μ	Fluorine coating(colored)

Table 8. The sectional constitutions of a FRP pipe

4.2 Analysis of loading test of a real-size site model

Before the loading test of the PSC box girder with concrete-filled FRP struts, general study of real-size site model tests are conducted including geometry and sectional dimension, a sensor attachment location and type, loading method and location, loading equipment constitution and design. The loads are calculated based on the DB-24 designated truck load and the responses are measured at FRP strut, slab, and edge beam. The length of specimens is 5m and struts are installed at both side. All dimensions are exactly same with actual structure.

(a) one axis loading

(b) two axis loading

(c) loading jig at the side of the upper plate acting reaction force

Fig 3. The front view of loading test

In order to study on the behavior of struts, top slab and edge beam in the PSC box girder with FRP struts, 5 load cases are defined

Case	Contents	Remark
LC 1	Longitudinal and transverse behavior of top slab	1 point loading
LC 2	Longitudinal behavior of edge beam	
LC 3	Compressive and flexural behavior of strut	
LC 4 LC 5	Description of vehicle load corresponding LC2 and LC3	2 points loading

Table 9. Mainly considered structural members & behavior for 5 load cases

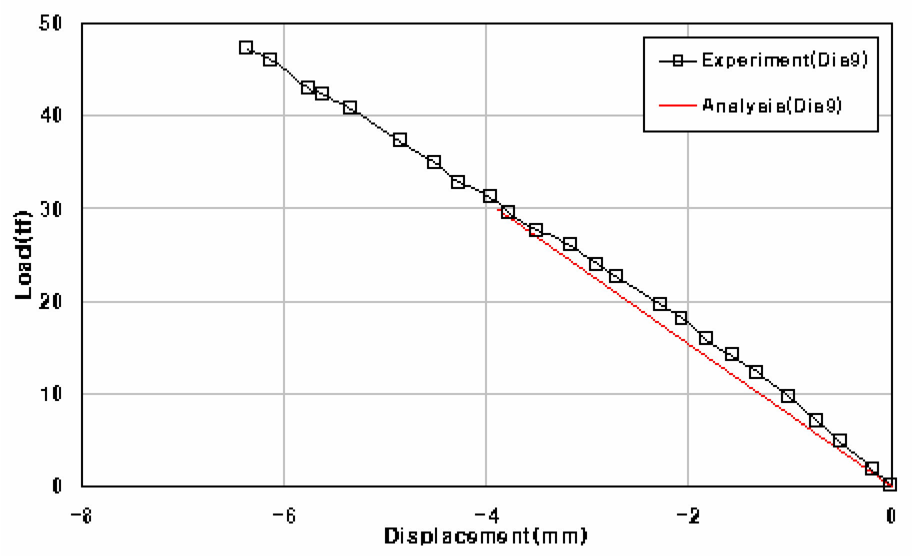
In every load cases, one and two axis loading are examined. The loading test equipment of a real-size site model consists of loading plate, oil pressure jack, loading jig, steel pipe, anchor bolt

and upper plate acting reaction force. Applied load is approximately twice bigger than the maximum equivalent design load to examine the behavior of real bridge.

4.3 Analysis of test results in 5 load cases

Load Case 1

The location of LC1 is determined to evaluate the stability of the top slab concrete which is



supported by struts from the web of a box girder.

Fig 4. The load-displacement curve at the top slab

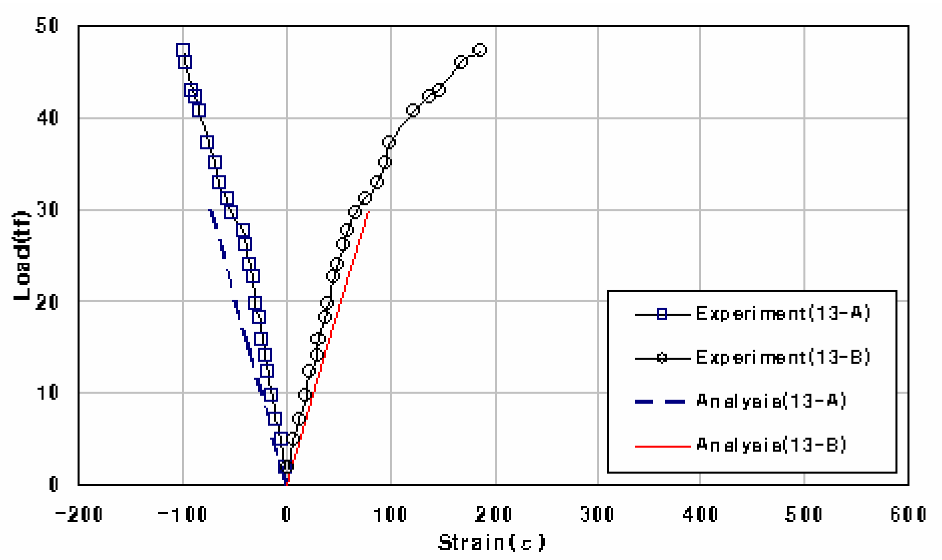


Fig 5. The load-strain curve at the transverse top slab

Load Case 2

The location of LC2 is on the strut supporting the top slab and the midpoint of an edge beam between struts, and that of LC2 is considered to analyze the behavior of a strut and longitudinal behavior of an edge beam.

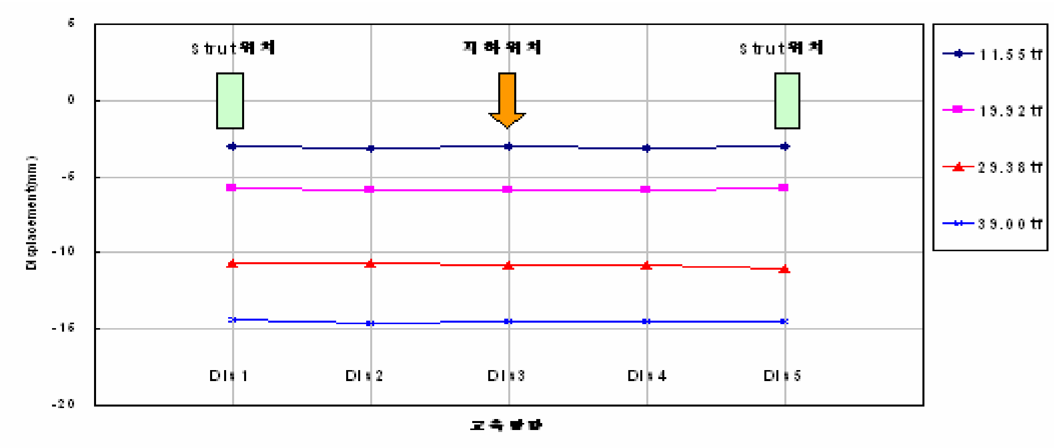


Fig 6. The displacement of the edge beam during loading

Load Case 3

LC3 is one point loading acting on upper strut which is supporting top slab, and the location of LC3 is determined to evaluate the safety of strut

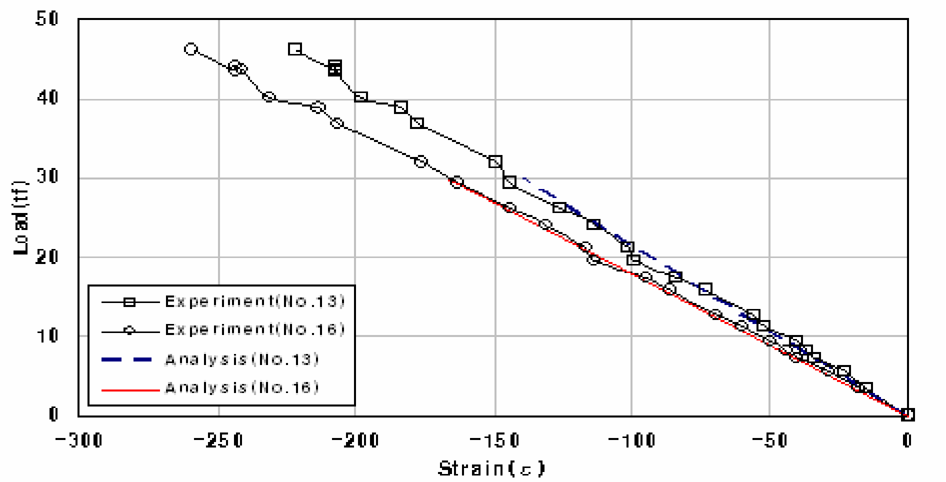


Fig 7. The load-strain relation at the lower part of strut

In order to evaluate the stability of PSC box girder bridge with FRP struts, the loading tests of a real-size site model are conducted. And the results of the loading tests and FEM analyses are as follows;

1. The PSC box girder and FRP strut ensure the safety of strength & serviceability under design load.

2. The FEM analysis results are generally close to the test results, and both results ensure safety

under the design load and equivalent acting load.

3. According to the test result, the strain of rebar from the upper to the lower slab is linear under the acting load and it has sufficient load capacity to equivalent acting load which occurs maximum internal force in slab.

4. In case of edge beam, it has high rigidity because it shows generally uniform displacement against increasing load. And relatively large stress is occurred at midpoint of lower edge beam, but it ensures safety because the crack stress is happened above equivalent design load.

5. Conclusion

The PSC box girder section with FRP coating strut maximizes the efficiency, durability and appearance of the structures. The verification of structural function and stability using loading test of a real-size site model and the study of increasing strength due to adhesion between FRP and concrete are completed. And the detailed study for verification is conducted in field.
Application of MSS(Movable Scaffolding System) which is automated construction method and performed first in the world maximizes reduction of construction period and insurance of high quality.
Now, this First innovative method in Korea is being applied to bridge plans in many turn-key based projects. In the future, it would be competitive among other conventional bridge types with several advantages & characteristics, such as structural efficiency, economical efficiency and good appearance.
The core factors of this innovative bridge are summarized as follows;
- Material reduction: decrease 15% of super-structure and 50% of sub-structure compare to former bridge types.
- Development of simple MSS method.
- Economical design of long-span concrete bridge (60m span length).
- Innovative improvement of bridge appearance.

(a) Construction process using MSS method

(b) Daylight view

(c) Night view

Fig 8. The photo of bridge under construction (Incheon Bridge Approaching Road section 3)

Fig 9. The view of the completed bridge (Incheon Bridge Approaching Road section 3)